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SATELLITE POWER USING A MAGNETICALLY SUSPENDED FLYWHEEL STACK*

JAMES A. KIRK and DAVINDER K. ANAND

University of Maryland, Mechanical Engineering Department and The Systems Research Center, College Park, MD 20742 (U.S.A.)

Summary

This paper reports upon research activities, with magnetically suspended flywheels, that are being cooperatively conducted by TPI, Inc. and the University of Maryland for GSFC. The purpose of the effort is to critically examine and further the development of all the key technologies which impact the inertial energy storage system.

The results presented in this paper discuss the concept of a magnetically suspended flywheel as it applies to a 500 W h energy storage system. The proposed system is currently under hardware development and is based upon two "pancake" magnetic bearings arranged in a vertical stack.

Introduction

To effectively design a 500 W h flywheel energy storage device, several parameters concerned with the specifications, design goals, and applications of the device have to be known *a priori*. For spacecraft applications, it is important to minimize the mass and size of the device without sacrificing its energy storage capacity. Therefore, one design goal of the system is to maximize the SED (specific energy density). This SED should exceed that of electrochemical systems, which are, typically, 14 W h kg^{-1}. A system SED goal for a past 300 W h flywheel design [2 - 5] has been to exceed a value of 20 W h kg^{-1} or 9 W h lb^{-1}. This was the design goal used for the 500 W h energy storage system.

The proposed energy storage system is based on a "pancake" magnetic bearing stack as shown in Fig. 1. The magnetic bearings used in the stack have been discussed by Kirk and Studer [6, 7] and are a required element for a viable and efficient energy storage system. The acceleration of the flywheel or charge cycle (motor mode) must occur during a 60 min interval when the satellite is exposed to sunlight. The spindown of the flywheel or discharge

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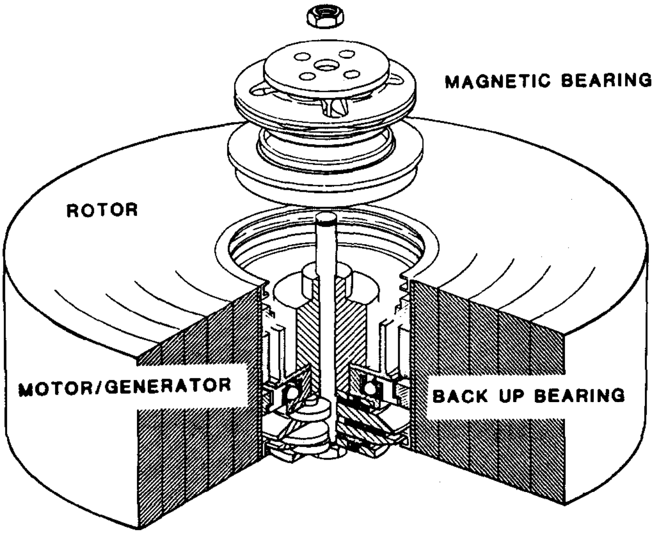

Fig. 1. Magnetic bearing stack for 500 W h system.

cycle (generator mode) must occur during a 30 min interval when the satellite is exposed to darkness. The energy storage system during discharge must supply power at a constant voltage of 150 ± 2% volts d.c. However, to design a flywheel with suitable size and capacity, operating speeds which are directly proportional to generator output voltages must vary by 50% (the high operating speed being twice as much as the low operating speed). Therefore, some type of power conditioning must be incorporated to maintain the required output voltage. In addition, energy losses in the electronics associated with the charge and discharge cycles must be minimized. For the 300 W h design, an efficiency of 90% for each cycle is desired. This was also assumed for the 500 W h design. Therefore to supply 500 W h, a 550 W h capacity flywheel was sized.

Other design goals of the system include modularity, suitability to withstand outside load disturbances, and protection of equipment when failure of flywheel material or suspension occur. An additional design criterion specifies that the rotor remain magnetically suspended under a 2 *g* radial load. This criterion is used in the 500 W h design. To protect the magnetic bearing, suspension ring, and motor/generator when failure of the magnetic suspension occurs, back-up ball bearings are used. The outside portion of the ball bearing (see Fig. 2) is set just beyond the gap operating range of the magnetic bearing (typically ±0.01 in.). The ball bearings support the flywheel when the flywheel deflection due to outside disturbances exceeds this operating range. They protect the magnetic bearing and motor/generator materials from collision. A detailed discussion on magnetic bearing back-up ball bearings is given in a paper by Frommer [2, 8]. For protection of satellite equipment if the flywheel material fails under high speeds (burst condition), it is necessary to design the flywheel for separation of the

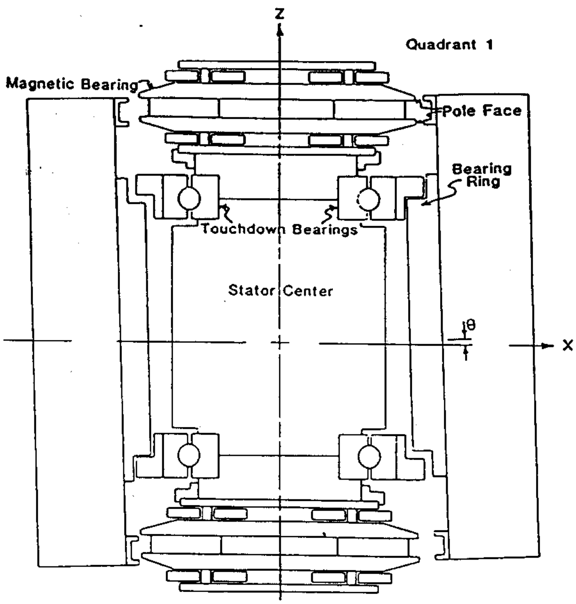

Fig. 2. Flywheel touchdown for a double magnetic bearing stack.

outermost rings from the remainder of the flywheel (as was done in refs. 9 - 14). Doing this makes the containment of failed flywheels easier.

Proposed flywheel design

The 500 W h capacity flywheel was analyzed using the FLYANS2/ FLYSIZE software developed by UMCP [11 - 13] and modified by TPI. The computer program FLYANS2 performs a stress analysis on a multi-ring flywheel arrangement, given material properties and inner radius ratios (inner radius of ring/outer radius of entire flywheel). Other inputs include the inner radius displacement ratio limit and the ring interference (in assembly) ratio limit. The inner radius displacement ratio input limits the gap growth (between the suspension ring of the flywheel and the magnetic bearing) of the suspension system due to the centrifugal forces generated by the spinning flywheel. Gap growth affects the suspension control system in a detrimental way by reducing the control system active stiffness, K_A. The ring interference limit is the limit on the amount of interference between rings. FLYANS2 performs a stress analysis for both non-interference fitted and interference-fitted rings. For interference fitted rings, it computes ring interface pressures that maximize SED while staying within a prescribed limit (typically 0.6%).

The data from FLYANS2 are used for the FLYSIZE computer program to actually size the flywheel. The FLYSIZE output for the 500 W h flywheel is shown in Table 1 with the upper and lower operating speed ratio, selected as 0.375 and 0.75 of the burst speed.

It is assumed that the flywheel has a weight of half the total energy storage system. Therefore its SED must be twice the system SED. Through repeated simulations, it was determined that a flywheel configuration with an inner return ring made of segmented iron and 5 composite (Celion 6000 graphite/epoxy) outer rings, interferenced fitted and having inner radius ratios (inner radius of ring/outer radius of outer ring of flywheel) of 0.48, 0.5, 0.6, 0.7, 0.8 and 0.9, yielded high SEDs that exceeded twice the system SED. The inner radius displacement ratio limit and the ring interference limit value used was 0.006. Repeated computer runs for a 500 W h flywheel with a high SED have yielded a flywheel configuration weighing approximately 29 lb.

The stack bearing consists of 2 magnetic bearings, a motor/generator, and 2 back-up ball bearings as shown in Fig. 1. One requirement for the flywheel is that it must have a large enough height to house the components shown in Fig. 1. Based on the sizing of the 300 W h flywheel system, the minimum component height for the 500 W h system is 4.50 in. (11.4 cm).

Flywheels incorporating 4 in., 5 in. and 6 in. (10.2 cm, 12.7 cm and 15.2 cm) magnetic bearings were analyzed and designed using the FLYANS2, FLYSIZE, and MAGBER computer programs. MAGBER, developed at UMCP, was used to determine the bearing's axial-load carrying capability. The results of design runs for flywheels using 4, 5 and 6 in. (10.2, 12.7 and 15.2 cm) dia. magnetic bearings are summarized in ref. 1.

As mentioned before, centrifugal forces cause the inner radius of the flywheel to expand at high speeds (called air gap growth). FLYSIZE deter-

TABLE 1

Flywheel specifications for 500 W h energy storage system

Inner diameter	5.760 in. (14.630 cm)
Outer diameter	12.000 in. (30.480 cm)
Thickness	5.474 in. (13.904 cm)
Configuration	*Multiring → 1 seg. iron ring* *5 graphite/epoxy rings*
Burst speed	70k r.p.m.
Max. oper. speed	52k r.p.m.
Low oper. speed	26k r.p.m.
Weight	29 lb (13.2 kg)
Usable energy density	18.96 W h lb^{-1} (41.71 W h kg^{-1})
Burst energy density	44.95 W h lb^{-1} (98.89 W h kg^{-1})
Air gap growth @ burst speed	0.0353 in. (0.8966 mm)
Air gap growth @ 52k r.p.m.	0.0199 in. (0.5055 mm)
Air gap growth @ 26k r.p.m.	0.0050 in. (0.1270 mm)

mines this expansion at the low and high operating speeds of the flywheel and reports these numbers to the user. Through iterative design runs using FLYANS2 and FLYSIZE, one can meet the air gap condition as well as achieve at high SED. The 500 W h design yielded an SED value of 19 W h lb^{-1} (42 W h kg^{-1}) and an air gap growth between lower and upper operating speeds of 0.015 in. (0.381 mm).

Magnetic bearing technology

The magnetic bearing for a 500 W h energy storage system was designed to support a 2 *g* axial load without loss of suspension. An additional goal was to achieve a certain permanent magnet radial stiffness, K_x, and current-force sensitivity, K_I. Design values for K_x and K_I were assumed based on maintaining suspension control system performance similar to past UMCP magnetic bearings.

Based on the UMCP 3 in. (7.6 cm) laboratory model, K_I was taken to be one hundredth the value of K_x in lb A^{-1}. Thus, for the 500 W h design, K_I was chosen to be 56 lb A^{-1}, while the value of K_x was chosen as 5600 lb $in.^{-1}$ (1002 kg cm^{-1}) with a flywheel linear excursion range (around a uniform air gap) of ±0.01 in. (±0.254 mm).

Knowing the desired system axial-load carrying capability, K_x, K_I, and maximum current, the following physical and magnetic properties of the bearing are then determined using the MAGBER design program:

Stator radius, air gap, permanent magnet (PM) area, PM thickness, PM operating point, leakage permeance, air gap permeance, air gap flux and flux density, coil turns, coil wire size and axial drop.

The sizing of the magnetic bearing involved an iterative process via computer simulation using the program MAGBER. Magnetic circuit permeances, fluxes, and flux densities were computed for trial physical dimensions (*i.e.*, pole face thickness, gap distance, axial drop, magnet area, magnet length) and material magnetic properties of the bearing. The operating flux density of the permanent magnets was also derived. K_x, K_I, coil turns (N), and axial-load carrying capability (W_a) could then be determined using the computed magnetic circuit parameters.

Based upon the trial dimensions, pole face thickness and air gap distance were increased to avoid saturation in the iron material (which limits the amount of useful flux that crosses the suspension air gap). The flux density within the Fe material should not exceed the value of 1.5 T or saturation will occur. The maximum flux density of the iron material was determined by computing the flux density at the thinnest portion of the flux plates, *i.e.*, at the pole faces. MAGDESIGN (a program developed at TPI for this project) was used to determine saturation conditions for various displacements of the flywheel. The object was to remain at an unsaturated condition within the operating gap range of the suspension control system.

Suspension control system design

The design goal for the suspension control system for the 500 W h energy storage system was to design a control system which would keep the flywheel suspended under static and dynamic loads. To withstand static loads (in this case a 2 *g* radial load), a system gain was selected which provided a steady state active stiffness sufficient to satisfy the required operating excursion range of the flywheel.

Nearly all of the electronic component values from previous UMCP laboratory suspension control systems were used in the design of the 500 W h control system. A schematic of the control system for the magnetic bearing is shown in Fig. 3.

The input reference voltage was determined to be within the range 0 - +15 V, which was the range used in past systems. The maximum operating current was used to size the coil wire and the power amplifiers. To minimize the control current and yet maintain the same steady state active stiffness the current-force sensitivity K_I was increased and the adjustable reference voltage was reduced by the same proportion. By increasing K_I the amount of coil turns needed for design was increased. For a value of $R_{17} = 11$ kΩ and $K_I = 56$ lb A^{-1} (25.5 kg A^{-1}), N was computed to have a value of 825 turns/coil, with a maximum operating current of 10.12 A. K_I was then increased by a factor of 2.5 to reduce the coil amperage to 4.05 A and reduce the variable resistance to 4360 Ω. This resulted in a K_I value of 140 lb in.$^{-1}$ (25 kg cm^{-1}) and a turns/coil value, N, of 2100 turns. The modified values were used for the 500 W h design.

The final parameter that was determined for the suspension control system was the compensation network time constant, T. This parameter influences the damping of the system. For the 500 W h system, it was desirable to maximize the damping so as to limit the flywheel excursions due to mass unbalance. To maximize system damping and minimize dynamic loading effects, an optimum value of T was selected. To optimize T, root locus plots and Bode plots were used, and the results are given in ref. 1.

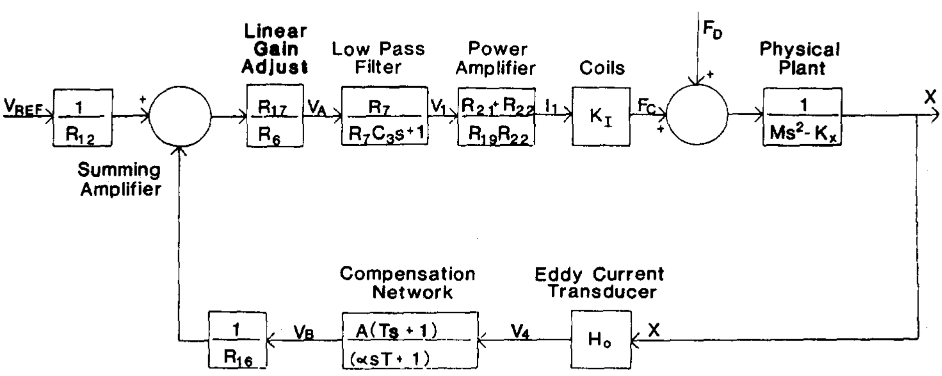

Fig. 3. Control system for magnetic suspension.

For the 500 W h system, a value of $T = 0.0016$ s was chosen to minimize the amplitude of response and maximize damping. This called for a capacitance value of 0.016 μF in the compensation network of the control system (keeping the resistance the same as previous values of past systems).

Based upon experience gained in designing the control system shown in Fig. 3, a modified version of the control system, as shown in Fig. 4, is being currently investigated for use in the 500 W h system.

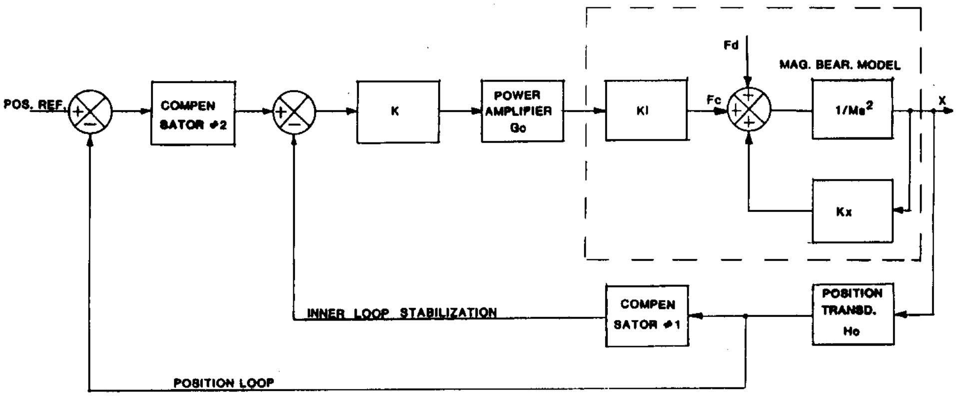

Fig. 4. Control system for 500 W h design.

Motor/generator design

The motor/generator design for the 500 W h system is based upon a permanent magnet, electronically commutated, 3-phase machine, shown conceptually in Fig. 5. Several improvements in the conceptual design have been incorporated into the 500 W h system, and these are shown in Fig. 6.

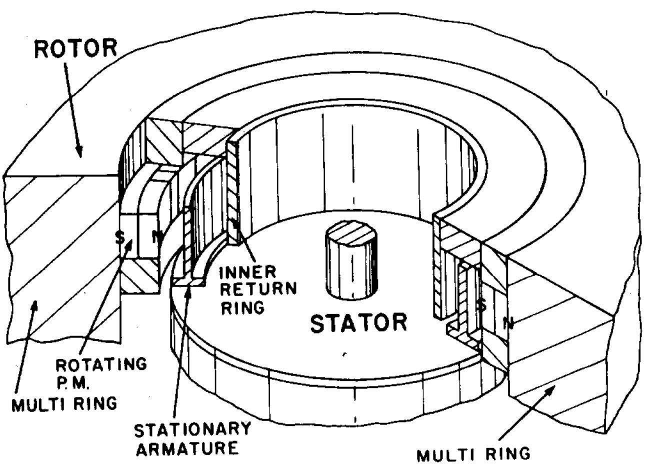

Fig. 5. Laboratory model of permanent magnet motor/generator.

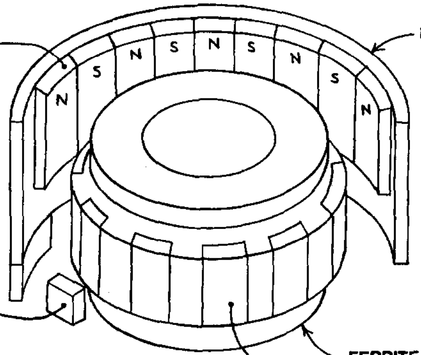

Fig. 6. Motor/generator design for 500 W h system.

The first step in design was to determine power, voltage, and armature current variation during the charge cycle of the motor and the discharge cycle of the generator. It was assumed that the bus of the motor receives a constant power of 650 W from the solar array at 150 V ± 2% d.c. This happens durring the time span of an hour. Since motor voltage is proportional to flywheel speed and flywheel speed was chosen to vary by 50%, a motor voltage profile varying from 70 V to 140 V was used in the design. (This assumed a voltage drop of 10 V during transfer of energy from *PV* array to flywheel motor.)

Armature current variation (per phase) was determined by dividing the time equation of power by the time equation of voltage. At the beginning of the charge cycle, the armature current/phase was computed to be 3.1 A and at the end it was computed to be 1.4 A. A proportional discharge cycle was assumed such that over 21 min, the generator discharges at a low power of 625 W and over the remaining 9 min the generator discharges at a high power of 1875 W. Altogether, the generator delivers 1100 W over 0.5 h, equal to 550 W h. 500 W h actually gets to the satellite power system due to energy losses in the power electronics. (This was a previously mentioned design goal.) The voltage variation of the generator is linear from 140 V to 70 V, but it varies at two different rates due to the change in power delivered. It was determined that the maximum current in the armature per phase is 8.93 A/phase.

This maximum current (which exceeds that of the motor) is used to design the coils in the armature. In the proposed motor/generator, the rotating ring will be replaced by a stationary ferrite ring glued onto the inside periphery of a stationary ironless armature. The outside rotating ring assembly is made up of PM and is attached to a soft iron backing ring. An 8-pole machine is proposed using a delta-connected winding operating at 4000 Hz maximum frequency. The dimensions of the device are constrained by the size of the flywheel and the magnetic bearing. For the 500 W h design, the outside radius of the soft iron backing ring could not exceed the inner radius of the first composite ring of the flywheel. A 2 in. packaging height was a design goal. The gap distance between PM's and armature coils needed also to exceed the gap distance of the magnetic bearing. Based on these constraints, PM size, and armature coil configuration and size were determined.

Of further interest is the determination of energy losses within the armature and also within the power electronics of the device. Armature loss ($3I^2_{max}R$) was computed to be 2.11 W, while the loss due to the ferrite ring was determined to be negligible (less than 1 W). Most of the other losses for the 500 W h energy storage system were kept the same as, or scaled up from, the 300 W h design.

500 W h design

The proposed design of the 500 W h magnetically suspended flywheel energy storage system is shown in Fig. 7. The specifications of the entire system are summarized in Tables 1 and 2.

Table 1 summarizes flywheel specifications computed using the FLY-SIZE/FLYANS2 software. Table 2 gives magnetic bearing specifications which were determined using magnetic circuit theory and the design programs previously discussed.

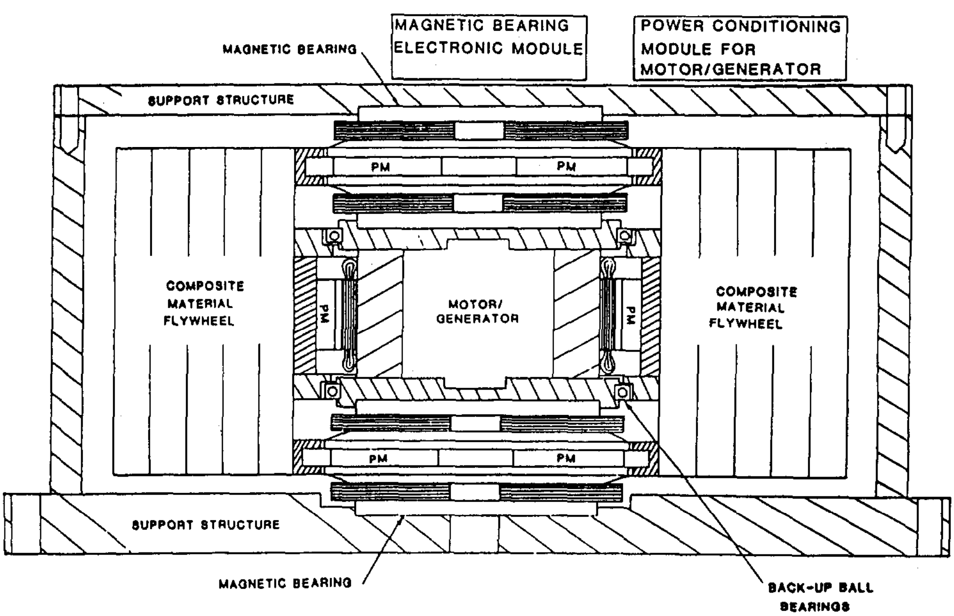

Fig. 7. Cross-section of 500 W h flywheel energy storage system.

TABLE 2

Magnetic bearing specifications for 500 W h energy storage system

Radial stiffness, K_x	5600 lb in.$^{-1}$ (1002 kg cm^{-1})
Current-force sensitivity, K_I	140 lb in.$^{-1}$ (25.1 kg cm^{-1})
Turns/electromagnetic coil, N	2100 turns
Maximum operating current, i_{max}	4.05 A
Gap operating range	±0.01 in. (±0.254 mm)
Nominal gap distance, g_o	0.038 in. (0.965 mm)
Stator radius	2.88 in. (7.32 cm)
Pole face thickness	0.15 in. (0.38 cm)
Magnet diameter	1.8 in. (4.57 cm)
Magnet length	0.3 in. (0.76 cm)

Conclusions/recommendations

Based upon the state-of-the-art review and the proposed design of the 500 W h system, it can be concluded that:

- Magnetically suspended flywheel energy storage systems are a viable and potentially superior alternative to batteries.
- System issues of attitude control and power transfer are manageable.
- The magnetically suspended flywheel system can be designed, using current knowledge, in modules varying in size from 100 W h to 1000 W h.

Consistent with these conclusions, the following activities are currently underway:

- Construct a Prototype 500 W h Energy Storage System using the proposed design.
- Bench test prototype to 20 000 r.p.m.
- Enhance robustness of control electronics based on bench testing.
- Design a test program to cycle energy storage wheel through operating range.
- Construct a Spin Test Facility for cyclic testing at design speeds.
- Test and evaluate prototype operation under design conditions. Incorporate test results in final design.
- Construct a flight hardware experiment.

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